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Unraveling the dynamics of magmatic CO_2 degassing at Mammoth Mountain, California

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ABSTRACT

The accumulation of magmatic CO_2 beneath low-permeability barriers may lead to the formation of CO_2-rich gas reservoirs within volcanic systems. Such accumulation is often evidenced by high surface CO_2 emissions that fluctuate over time. The temporal variability in surface degassing is believed in part to reflect a complex interplay between deep magmatic degassing and the permeability of degassing pathways. A better understanding of the dynamics of CO_2 degassing is required to improve monitoring and hazards mitigation in these systems. Owing to the availability of long-term records of CO_2 emissions rates and seismicity, Mammoth Mountain in California constitutes an ideal site towards such predictive understanding. Mammoth Mountain is characterized by intense soil CO_2 degassing (up to $\sim$1000 $\mathrm{t\,d^{-1}}$) and tree kill areas that resulted from leakage of CO_2 from a CO_2-rich gas reservoir located in the upper $\sim$4 km. The release of CO_2-rich fluids from deeper basaltic intrusions towards the reservoir induces seismicity and potentially reactivates faults connecting the reservoir to the surface. While this conceptual model is well-accepted, there is still a debate whether temporally variable surface CO_2 fluxes directly reflect degassing of intrusions or variations in fault permeability. Here, we report the first large-scale numerical model of fluid and heat transport for Mammoth Mountain. We discuss processes (i) leading to the initial formation of the CO_2-rich gas reservoir prior to the occurrence of high surface CO_2 degassing rates and (ii) controlling current CO_2 degassing at the surface. Although the modeling settings are site-specific, the key mechanisms discussed in this study are likely at play at other volcanic systems hosting CO_2-rich gas reservoirs. In particular, our model results illustrate the role of convection in stripping a CO_2-rich gas phase from a rising hydrothermal fluid and leading to an accumulation of a large mass of CO_2 ($\sim 10^7$–10^8 t) in a shallow gas reservoir. Moreover, we show that both, short-lived (months to years) and long-lived (hundreds of years) events of magmatic fluid injection can lead to critical pressures within the reservoir and potentially trigger fault reactivation. Our sensitivity analysis suggests that observed temporal fluctuations in surface degassing are only indirectly controlled by variations in magmatic degassing and are mainly the result of temporally variable fault permeability. Finally, we suggest that long-term CO_2 emission monitoring, seismic tomography and coupled thermal–hydraulic–mechanical modeling are important for CO_2-related hazard mitigation.

1. Introduction

Globally, temporal variations in diffuse volcanic CO_2 emissions have been attributed to mechanisms such as magma and/or magmatic fluid injection, change in crustal permeability and meteorological forcing (e.g., Rogie et al., 2001; Hernandez et al., 2001; Granieri et al., 2010; Arpa et al., 2013; Melian et al., 2014; Lewicki et al., 2014; Werner et al., 2014). In the particular case where volcanic systems host large volumes of CO_2-rich gas beneath low-permeability barriers (e.g. Albani Hills and Latera Caldera, Italy; Dieng Volcanic complex, Indonesia; Mammoth Mountain, USA), temporal variations in CO_2 emissions may result from a complex, yet poorly understood interplay between injection of magmatic CO_2 from below and the permeability of faults controlling CO_2 migration from the reservoir to the surface (e.g., Allard et al., 1989; Annunziatellis et al., 2008; Carapezza et al., 2012; Lewicki et al., 2014; Werner et al., 2014). Accumulation of CO_2 in the near surface may cause vegetation stress and the death of animals (Beaubien et al., 2008; Carapezza et al., 2012). Human fa-

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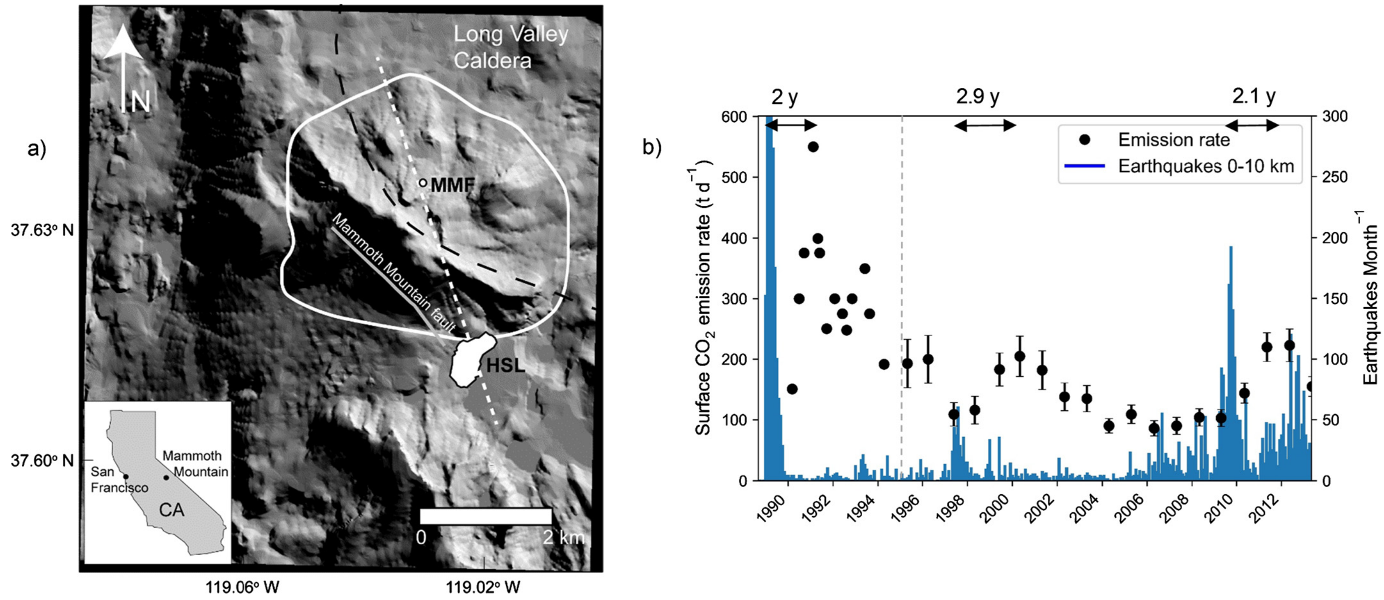

Fig. 1. (a) Relief map showing the location of Mammoth Mountain (white line), the Horseshoe Lake tree kill area (HSL) and the Mammoth Mountain fumarole (MMF). The dashed black line corresponds to the location of the Long Valley caldera rim, while the gray line shows the Mammoth Mountain fault trace. The modeled cross-section is represented by the dashed white line. (b) Time series of surface CO_2 emission rate ($t\,d^{-1}$) at HSL and number of shallow earthquakes (<10 km depth) per month (modified from Werner et al., 2014). Arrows show time delays between major seismic events and degassing peaks. Direct measurements of CO_2 emissions were not performed until 1995 (dashed line). The pre-1995 flux data were extrapolated from measurements of steam flux at MMF and considering average steam to CO_2 emission ratio, while post-1995 data correspond to CO_2 emission rates calculated based on direct CO_2 flux measurements using the accumulation chamber method. Error bars associated with post-1995 data correspond to one standard deviation of the mean emissions.

talities have also been reported, for example, at Mammoth Mountain, California (Hill, 2000), Lakes Monoun and Nyos, Cameroun (Sigurdsson, 1987; Tazieff, 1989; Giggenbach et al., 1991), and Dieng Volcanic Complex, Indonesia (Allard et al., 1989). A predictive understanding of volcanic CO_2 emissions is therefore fundamental to develop adequate monitoring strategies. Over the past decades, numerical modeling of fluid and heat transport has evolved towards such a predictive tool and numerous applications to volcanic systems are found in the literature (e.g. Hurwitz et al., 2003; Costa et al., 2008; Ingebritsen et al., 2010; Todesco et al., 2010; Chiodini et al., 2016). The number of modeling studies simulating episodic CO_2-dominated degassing at volcanic systems, however, is still limited and the general understanding of such systems is solely based on a qualitative conceptual model involving the presence of CO_2-rich gas reservoirs or pockets in the subsurface (Giggenbach et al., 1991).

Here we present a numerical modeling study of the dynamics of magmatic CO_2 degassing at Mammoth Mountain (California). Owing to the availability of long-term records of CO_2 emissions rates and seismicity (Werner et al., 2014 and references therein), Mammoth Mountain constitutes an ideal site for gaining more quantitative insight into the CO_2 degassing dynamics of volcanic systems. In particular, we evaluate the processes that (i) favor the formation of large scale CO_2-rich gas reservoirs within the shallow subsurface, and (ii) subsequently control CO_2 emission rates at the surface. Moreover, we discuss the implications of our results in terms of volcanic monitoring and hazard mitigation.

2. Site description

Mammoth Mountain is a dacitic volcano located on the southwestern rim of the Long Valley caldera in California (Fig. 1a). In 1989, Mammoth Mountain transitioned to a state of unrest marked by an 11 month-long low-magnitude ($M \leq 3$) seismic swarm and the onset of intense non-thermal (i.e., cold) CO_2 soil degassing. This led to the formation of areas of tree kill on the volcano flanks, amongst which the Horseshoe Lake tree kill (HSL) is the largest (0.28 km^2) (e.g., Hill and Prejean, 2005). Over the next two decades, further swarms (e.g., 1997, 2006, 2008, 2009, 2011, 2014) occurred and surface degassing fluctuated significantly. Interestingly, CO_2 degassing maxima occurred two to three years after the onset of the 1989, 1997 and 2009 swarms (Fig. 1b).

The conceptual model for explaining such long-term degassing involves a laterally extensive, shallow (<5 km) CO_2-rich gas reservoir, which is overlain by a low-permeability caprock or zone of hydrothermal alteration (Sorey et al., 1998). Gas geothermometry predicts a gas reservoir temperature of ~150 °C (Sorey et al., 1998). Furthermore, a liquid dominated hydrothermal system was postulated to occur beneath the gas reservoir (Sorey et al., 1998). The origin of CO_2 in the reservoir is attributed to the long-term degassing of basaltic intrusions at greater depth (>10 km), while the observed seismicity is believed to reflect increases in pore pressure associated with the episodic migration of CO_2 from the magmatic intrusion towards the shallow reservoir and the surface. Using a model linking pore geometry and fluid compressibility to Vp/Vs ratios (Takei, 2002), Dawson et al. (2016) estimated the total mass of CO_2 within the shallow gas reservoir as 4.6×10^6 to 1.9×10^8 tons (t).

Although short-term (month-to-month) variations in observed CO_2 emissions at HSL were attributed in part to meteorological forcing, Werner et al. (2014) assumed that the long-term (inter-annual) variations (Fig. 1b) largely reflected deep processes. However, there is still a debate regarding the controls on the observed variation in CO_2 emission rates. On the one hand, Werner et al. (2014) suggested that these oscillations reflect pressurization events caused by changes in the intensity of the magmatic CO_2 input to the reservoir. They excluded the possibility that CO_2 flux oscillations were directly related to changes in permeability of the faults connecting the reservoir to the tree-kill areas. Accordingly, the time lag between major seismic events and maximum surface degassing corresponds to the time required for the CO_2-saturated fluid to ascend from the reservoir to the surface. On the other hand, Lewicki et al. (2014) invoked a permeability control to explain why certain seismic swarms (e.g., 1989, 2009) were